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ESTIMATING C_n^2, C_t^2, C_{tq}, AND C_q^2 DURING UNSTABLE ATMOSPHERIC CONDITIONS

August 1991

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The purpose of this report is to present the authors' development of expressions for the refractive index structure parameters C_n^2, C_t^2, C_{tq}, and C_q^2 and the similarity functions g_t (z/L), g_q (z/L), and g_n (z/L). The authors also compare their expressions with those of Andreas and Wyngaard. Finally they compare their results for C_n^2 with those of Wesely.

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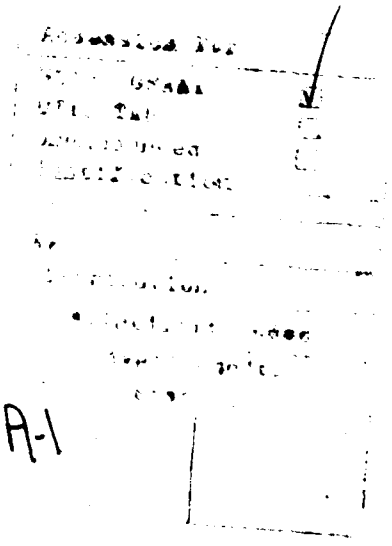

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1. INTRODUCTION

Andreas (1988) in referencing Wyngaard et al. (1971) states that the structure parameter C_t^2 should have a universal form when properly scaled, that is,

$$\frac{C_t^2 \, z^{2/3}}{t_*^2} = g_t \left[\frac{z}{L}\right] \tag{1}$$

Where, for unstable conditions,

$$g_t \left[\frac{z}{L}\right] = 4.9 \left[1 - 6.1 \, \frac{z}{L}\right]^{-2/3} \tag{2}$$

z = height

t_* = temperature scaling length

L = Obkuhov (1946) length

Andreas also notes that Fairall et al. (1980a) and Kohsiek (1982) extended these arguments to the humidity structure parameter C_Q^2 and to the temperature–humidity structure parameter C_{tQ} obtaining

$$\frac{C_Q^2 \, z^{2/3}}{Q_*^2} = g_q \left[\frac{z}{L}\right] \tag{3}$$

and

$$\frac{C_{tQ} \, z^{2/3}}{t_* \, Q_*} = g_{tq} \left[\frac{z}{L}\right] \tag{4}$$

where,

Q = absolute humidity (grams per cubic meter)

Q_* = absolute humidity scaling length

Andreas further suggests that C_n^2 should exhibit the characteristics of C_t^2, C_Q^2, and C_{tQ} since it can be shown that

$$C_n^2 = A^2 \, C_t^2 + 2 \, A \, B \, C_{tQ} + B^2 \, C_Q^2 \tag{5}$$

where A and B are derived from a real index of refraction fluctuation expression that varies with wavelength. Consistent with the above formulations and concepts, Andreas developed a similarity expression for the real index of refraction fluctuations,

$$n_* = A\, t_* + B\, Q_* \tag{6}$$

and concludes that C_n^2 should have the form

$$\frac{C_n^2\, z^{2/3}}{n_*^2} = g_n\left(\frac{z}{L}\right) \tag{7}$$

Later in his report, Andreas (1988) concludes and Hill (1989) proves that

$$g_t\left(\frac{z}{L}\right) = g_q\left(\frac{z}{L}\right) = g_{tq}\left(\frac{z}{L}\right) = g_n\left(\frac{z}{L}\right) = g\left(\frac{z}{L}\right) \tag{8}$$

We wish to emphasize that up to this point in this report that Q represents moisture in absolute humidity form; whereas, in later developments we will use q (specific humidity) to be constant with Tatarski's (1961) original derivations of C_n^2.

The purpose of this report is to present our development of expressions for C_t^2, C_{tq}, C_q^2, C_n^2, $g_t\left(\frac{z}{L}\right)$, $g_q\left(\frac{z}{L}\right)$, $g_{tq}\left(\frac{z}{L}\right)$, *and* $g_n\left(\frac{z}{L}\right)$; comparisons with those in Andreas; and comparisons of C_n^2 with Wesely (1976).

2. RACHELE/TUNICK (RT) FORMULATIONS

We initiate our development using Tatarski's expression for C_n^2, that is,

$$C_n^2 = b\left(\frac{K_H}{\epsilon^{1/3}}\right)\left(\frac{dn}{dz}\right)^2 \tag{9}$$

where,

b = constant = 3.2 (Wyngaard (1973), Hill (1989), Andreas (1988))

$$K_H = \frac{u^*\, k\, z}{\phi_H} = \textit{turbulent exchange coefficient for heat} \tag{10}$$

$$\epsilon = \frac{u^{*3}}{kz}\left(\phi_M - \frac{z}{L}\right) = \textit{energy dissipation rate} \tag{11}$$

$$\phi_H = \left(1 - \gamma \frac{z}{L}\right)^{-1/2}, \; L < 0 \tag{12}$$

$$\phi_M = \left(1 - \beta \frac{z}{L}\right)^{-1/4}, \; L < 0 \tag{13}$$

k = Karman's constant (0.4)

u^* = friction velocity

$\gamma = \beta = 15$ (Hansen, 1980)

$\frac{dn}{dz}$ = the gradient of the real index of refraction in the vertical direction z.

Andreas' (1988) expression for n with moisture in absolute humidity is

$$n = A\,(\lambda, P, T, Q)\,T + B\,(\lambda, P, T, Q)\,Q, \tag{14}$$

where for $\lambda = 0.55\ \mu m$

$$A = -7.9 \times 10^{-5}\ \frac{P}{T^2}$$

$$B = -5.46 \times 10^{-5}$$

and where P and T are pressure in millibars and temperature in K.

In our notation we write equation (14) as

$$dn = A\,(\lambda, P, T, q)\,dT + B_q\,(\lambda, P, T, q)\,dq \tag{15}$$

where,

$$A = -7.9 \times 10^{-5} \frac{P}{T^2}$$

$$B_q = -1.97 \times 10^{-5} \frac{P}{T}$$

q = specific humidity

Dividing equation (15) by dz gives

$$\frac{dn}{dz} = -7.9 \times 10^{-5} \frac{P}{T^2} \frac{dT}{dz} - 1.97 \times 10^{-5} \frac{P}{T} \frac{dq}{dz} \tag{16}$$

Furthermore, equation (5), in terms of specific humidity, becomes

$$C_n^2 = A^2 C_t^2 + 2 A B C_{tq} + B_q^2 C_q^2. \tag{17}$$

For unstable homogeneous conditions, we let

$$\frac{dT}{dz} = \frac{\partial \theta}{\partial z} \text{ and } \frac{dq}{dz} = \frac{\partial q}{\partial z} \tag{18}$$

Substituting equation (18) into equation (16) gives

$$\frac{dn}{dz} = -7.9 \times 10^{-5} \frac{P}{T^2} \frac{\partial \theta}{\partial z} + -1.97 \times 10^{-5} \frac{P}{T} \frac{\partial q}{\partial z} \tag{19}$$

or

$$\frac{dn}{dz} = -7.9 \times 10^{-5} \frac{P}{T^2} \frac{\partial \theta}{\partial z} - (1.975 \times 10^{-5} T) \frac{P}{T^2} \frac{\partial q}{\partial z} \tag{20}$$

Squaring equation (20) gives

$$\left(\frac{dn}{dz}\right)^2 = 6.241 \times 10^{-9} \frac{P^2}{T^4} \left(\frac{\partial \theta}{\partial z}\right)^2$$

$$+ \left[3.11 \times 10^{-9} T\right] \frac{P^2}{T^4} \cdot \frac{\partial \theta}{\partial z} \frac{\partial q}{\partial z} \qquad (21)$$

$$+ \left[3.88 \times 10^{-10} T^2\right] \frac{P^2}{T^4} \left(\frac{\partial q}{\partial z}\right)^2$$

Expressing $\frac{\partial \theta}{\partial z}$ and $\frac{\partial q}{\partial z}$ in equation (21) in similarity form, for unstable conditions, that is,

$$\frac{\partial \theta}{\partial z} = \frac{\theta^*}{kz} \left(1 - \gamma \frac{z}{L}\right)^{-1/2} \qquad (22)$$

equation (21) becomes

$$\frac{\partial q}{\partial z} = \frac{q^*}{kz} \left(1 - \gamma \frac{z}{L}\right)^{-1/2} \qquad (23)$$

$$\left(\frac{dn}{dz}\right)^2 = 6.241 \times 10^{-9} \frac{P^2}{T^4} \frac{\theta^{*2}}{k^2 z^2} \left(1 - \gamma \frac{z}{L}\right)^{-1}$$

$$+ 3.11 \times 10^{-9} T \frac{P^2}{T^4} \frac{\theta^* q^*}{k^2 z^2} \left(1 - \gamma \frac{z}{L}\right)^{-1} \qquad (24)$$

$$+ 3.88 \times 10^{-10} T^2 \frac{P^2}{T^4} \frac{q^{*2}}{k^2 z^2} \left(1 - \gamma \frac{z}{L}\right)^{-1}$$

where

γ = constant

$$L = \frac{u^{*2} T(1 + 0.61\, q)}{kg\, (\theta^* + 0.61\, \theta\, q^*} \qquad (25)$$

g = acceleration of gravity.

Substituting equation (24) into equation (5) and (9) gives

$$C_n^2 = A' \theta^{*2} + B' \theta^* q^* + C' q^{*2} \tag{26}$$

where

$$A' = b \left(\frac{K_H}{\epsilon^{1/3}}\right) 6.241 \times 10^{-9} \frac{P^2}{T^4 k^2 z^2} \left(1 - \gamma \frac{z}{L}\right)^{-1} \tag{27}$$

$$B' = b \left(\frac{K_H}{\epsilon^{1/3}}\right) (3.11 \times 10^{-9} T) \frac{P^2}{T^4 k^2 z^2} \left(1 - \gamma \frac{z}{L}\right)^{-1} \tag{28}$$

$$C' = b \left(\frac{K_H}{\epsilon^{1/3}}\right) (3.88 \times 10^{-10} T^2) \frac{P^2}{T^4 k^2 z^2} \left(1 - \gamma \frac{z}{L}\right)^{-1} \tag{29}$$

$$K_H = \frac{k u^* z}{\left(1 - \gamma \frac{z}{L}\right)^{-1/2}} \tag{30}$$

$$\epsilon = \frac{u^{*3}}{kz} \left(\phi_M - \frac{z}{L}\right) \tag{31}$$

$$\phi_M = \left(1 - \beta \frac{z}{L}\right)^{-1/4} \tag{32}$$

From equations (30) through (32)

$$\frac{K_H}{\epsilon^{1/3}} = k^{4/3} z^{4/3} \left\{ \frac{\left(1 - \gamma \frac{z}{L}\right)^{1/2}}{\left[\left(1 - \beta \frac{z}{L}\right)^{-1/4} - \frac{z}{L}\right]^{1/3}} \right\} \tag{33}$$

Substituting equations (33) into equations (27), (28), and (29) gives

$$A' = b \left(6.241 \times 10^{-9} \frac{P^2}{T^4}\right) k^{-2/3} z^{-2/3} \left(1 - \gamma \frac{z}{L}\right)^{-1} \{\ \} \tag{34}$$

$$B' = b \left[3.11 \times 10^{-9} T\right] \cdot \frac{P^2}{T^4} k^{-2/3} z^{-2/3} \left(1 - \gamma \frac{z}{L}\right)^{-1} \{\ \} \tag{35}$$

$$C' = b \left(3.88 \times 10^{-10} T^2\right) \frac{P^2}{T^4} k^{-2/3} z^{-2/3} \left(1 - \gamma \frac{z}{L}\right)^{-1} \{\ \} \tag{36}$$

Equating equations (26) and (17) term by term gives

$$C_t^2 = \frac{A'}{A^2} \theta^{*2} \tag{37}$$

$$= b\, \theta^{*2} k^{-2/3} z^{-2/3} \left(1 - \gamma \frac{z}{L}\right)^{-1} \{\ \} \tag{38}$$

$$= b\, \theta^{*2} k^{-2/3} z^{-2/3} \left\{ \frac{\left(1 - \gamma \frac{z}{L}\right)^{-1/2}}{\left[\left(1 - \beta \frac{z}{L}\right)^{-1/4} - \frac{z}{L}\right]^{1/3}} \right\} \tag{39}$$

or

$$\frac{C_t^2 z^{2/3}}{\theta^{*2}} = b\, k^{-2/3} \left\{ \frac{\left(1 - \gamma \frac{z}{L}\right)^{-1/2}}{\left[\left(1 - \beta \frac{z}{L}\right)^{-1/4} - \frac{z}{L}\right]^{1/3}} \right\} = g_t \tag{40}$$

Similarly,

$$C_{tq} = \frac{B' \theta^* q^*}{2 A B_q} \tag{41}$$

$$\doteq b\ \theta^{*}q^{*}\ k^{-2/3}\left\{\ \right\} = g_{tq} \tag{42}$$

or

$$\frac{C_{tq}\ z^{2/3}}{\theta^{*}\ q^{*}} \doteq b\ k^{-2/3}\left\{\ \right\} = g_{tq} \tag{43}$$

Also

$$C_q^2 = \frac{C'\ q^{*2}}{B_q^2}$$

$$\doteq b\ q^{*2}\ k^{-2/3}\ z^{-2/3}\left\{\ \right\} \tag{44}$$

or

$$\frac{C_q^2\ z^{2/3}}{q^{*2}} = b\ k^{-2/3}\left\{\ \right\} = g_q \tag{45}$$

To account for moisture contributions to C_n^2, Kunkel and Walters (1983) used an expression by Wesely (1976), that is,

$$C_n^2 = C_t^2\ A^2\ (1 + 0.03/B_o)^2 \tag{46}$$

where

$$B_o = \textit{Bowen ratio} = 4 \times 10^{-4}\frac{\theta^{*}}{q^{*}} \tag{47}$$

In our model we relate C_n^2 to C_t^2 and B_o as follows. From equations (37) through (45) we write

$$C_t^2 = \theta^{*2}\ z^{-2/3}\ g_t \tag{48}$$

$$C_{tq} = \theta^* q^* z^{-2/3} g_{tq} = \theta^* q^* z^{-2/3} g_t \tag{49}$$

$$C_q^2 = q^{*2} z^{-2/3} g_q = q^{*2} z^{-2/3} g_t \tag{50}$$

Furthermore, from equations (48) through (50), we obtain

$$C_{tq} = \frac{q^*}{\theta^*} C_t^2 \frac{g_{tq}}{g_t} = \frac{q^*}{\theta^*} C_t^2 \tag{51}$$

$$C_q^2 = \frac{q^{*2}}{\theta^{*2}} \frac{g_q}{g_t} C_t^2 = \left(\frac{q^*}{\theta^*}\right)^2 C_t^2 \tag{52}$$

Substituting equations (51) and (52) into equation (17) gives

$$C_n^2 = A^2 C_t^2 \left[1 + \frac{B_q}{A} \frac{q^*}{\theta^*} + \left(\frac{B_q}{A}\right)^2 \left(\frac{q^*}{\theta^*}\right)^2\right] \tag{53}$$

or, in terms of B_o,

$$C_n^2 = A^2 C_t^2 \left[1 + \frac{B_q}{AB_o} + \frac{1.6 \times 10^{-7}}{B_o^2} \left(\frac{B_q}{A}\right)^2\right] \tag{54}$$

Substituting the values of A and B_q, given earlier (equation (15)), into equation (54) results in

$$C_n^2 \doteq A^2 C_t^2 \left[1 + \frac{1.99 \times 10^{-4}}{B_o} T + \frac{3.98 \times 10^{-8}}{B_o^2} T^2\right] \tag{55}$$

3. COMPARISONS

Wyngaard (1973) concluded from scaling laws and the analyses of Kansas data that

$$g_t(\zeta) = 4.9 (1 - 6.1\zeta)^{-2/3} \tag{56}$$

for $\zeta \leq 0$. Hill (1989) demonstrated that $g_t(\zeta) = g_{tq}(\zeta) = g_q(\zeta) = g_n(\zeta)$.

Andreas (1988) concluded that

$$g_b(\zeta) = \frac{5.92\phi_H(\zeta)}{\phi_\epsilon(\zeta)^{1/3}} \tag{57}$$

based on the budget equations where Wyngaard and Cote (1971), Kaimal et al. (1972), Fairall et al. (1980b), and Schacher et al. (1981) found that

$$\phi_e(\zeta) = \left[1 + 0.46(-\zeta)^{2/3}\right]^{3/2}, \; 2 \leq \zeta \leq 0 \tag{58}$$

$$\phi_e(\zeta) = \left[1 + 2.3\,\zeta^{3/5}\right]^{3/2}, \; 0 \leq \zeta \leq 2 \tag{59}$$

From the formulations in this study (equation (40)), we found that

$$g_t(\zeta) = \frac{5.89\phi_H(\zeta)}{\phi_\epsilon(\zeta)^{1/3}} \tag{60}$$

where, from Panofsky (1968), $\phi_e(\zeta)^{1/3} = (\phi_m - \zeta)^{1/3}$.

We also show that $g_t(\zeta) = g_q(\zeta) = g_{tq}(\zeta) = g_n(\zeta)$.

The functions $(1 - 6.1\zeta)^{-2/3}$, $\dfrac{\phi_H(\zeta)}{\left[1 + 0.46(-\zeta)^{2/3}\right]^{3/2}}$ *and* $\dfrac{\phi_H(\zeta)}{(\phi_m - \zeta)^{1/3}}$ are compared in figure 1; whereas, the complete functions

$4.9(1 - 6.1\zeta)^{-2/3}$, $\dfrac{5.92\phi_H(\zeta)}{\left[1 + 0.46(-\zeta)^{2/3}\right]^{3/2}}$, *and* $\dfrac{5.89\phi_H(\zeta)}{(\phi_m - \zeta)^{1/3}}$ are shown in figure 2.

Figure 3 illustrates resultant C_n^2 vertical profiles by using the three forms for $g(z/L)$ discussed above. Equations (6) and (7) describe the formulation for the profiles presented in figure 3.

Finally, we compare values of C_n^2/C_t^2 by using equations (46) and (55). These values are presented in figure 4.

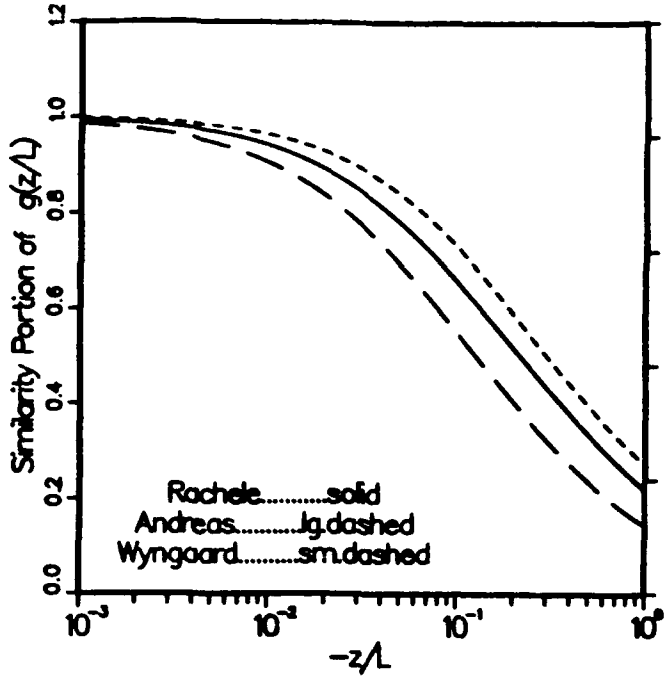

Figure 1. A comparison of the variations of the similarity portion of the function g (z/L).

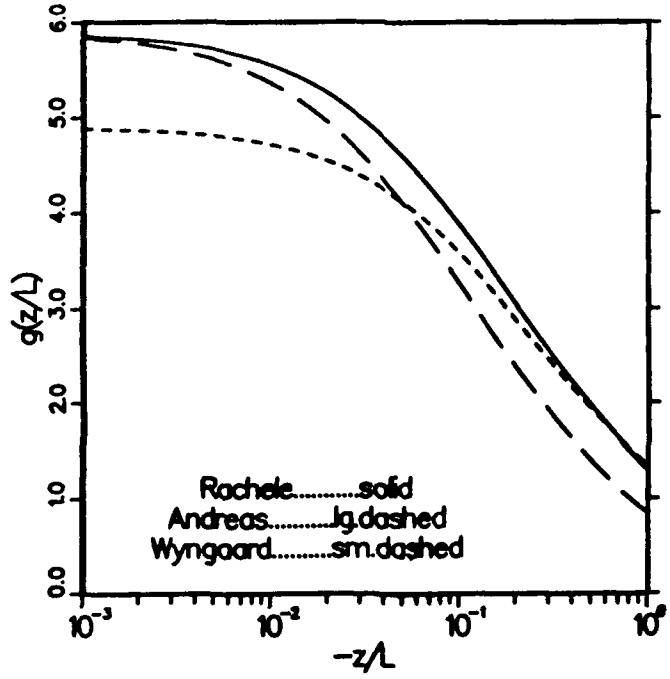

Figure 2. A comparison of the complete expressions of the function g (z/L).

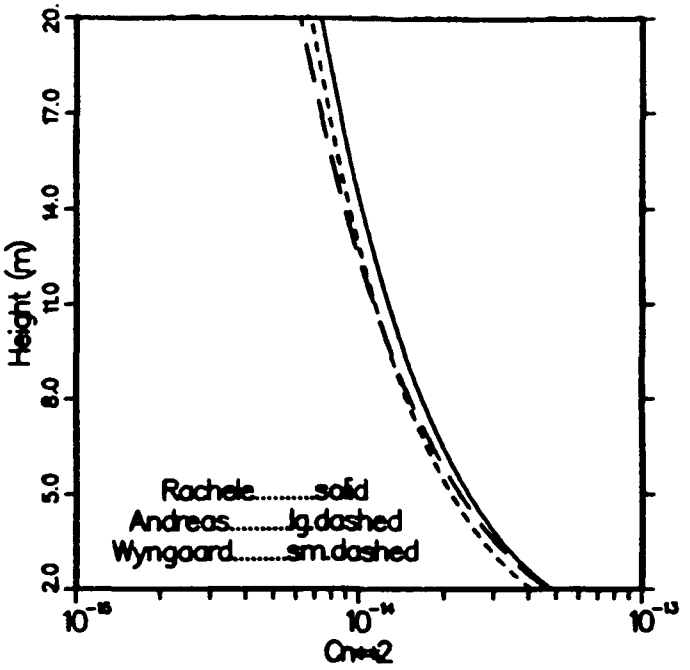

Figure 3. C_n^2 vertical profiles using the g (z/L) functions of Rachele, Andreas, and Wyngaard.

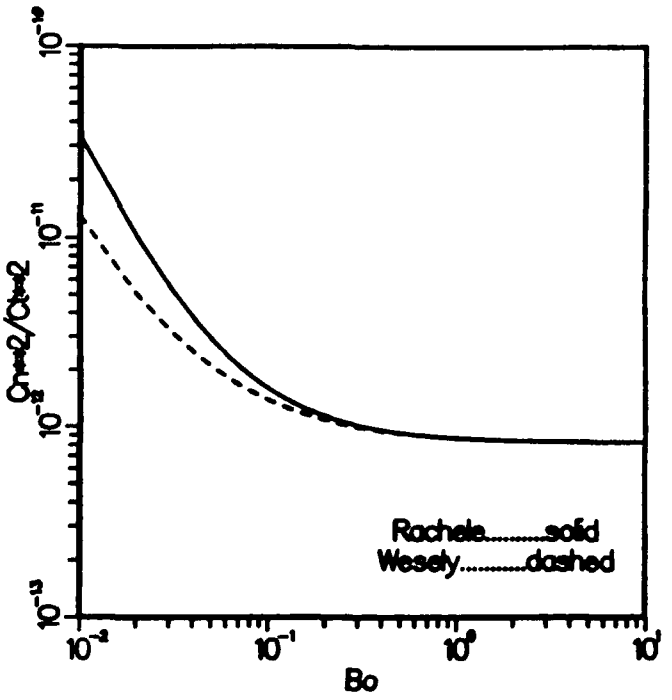

Figure 4. The ratio C_n^2/C_t^2 versus B_o (Bowen Ratio) for equations (46) (Wesely, 1976) and (55) (Rachele) for T = 296.15 K.

4. SUMMARY AND CONCLUSIONS

In this report, we have shown our development of expressions for the refractive index structure parameters, C_n^2, as well as the temperature and humidity structure function parameters C_t^2, C_q^2, and C_{tq}. We have also presented our development for the similarity functions g_t, g_{tq}, and g_q.

We concluded that the singular universal function g (z/L) satisfies the expression $g_t = g_{tq} = g_q = g$ as shown by equations (40), (43), and (45).

In figures 1 and 2 we show that as $|-\frac{z}{L}|$ increases in magnitude greater differences arose between the expressions for g_t of Andreas (1988), Wyngaard (1973), and Rachele. Clearly they are not equivalent.

However, much less separation is evidenced between the profiles of C_n^2 presented in figure 3. The choice of which g(z/L) function to use may now be less critical.

Finally, we compared values of the ratio C_n^2/C_t^2 by using equations from our development and those from Wesely (1976). Figure 4 shows that both expressions compare closely to one another.

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